Combined Effects of Constant versus Variable Intensity Simulated Rainfall and Reduced Tillage Management on Cotton Preemergence Herbicide Runoff

Thomas L. Potter,* Clint C. Truman, Timothy C. Strickland, David D. Bosch, Theodore M. Webster, Dorcas H. Franklin, and Craig W. Bednarz

ABSTRACT

Pesticide runoff research relies heavily on rainfall simulation experiments. Most are conducted at a constant intensity, i.e., at a fixed rainfall rate; however, large differences in natural rainfall intensity is common. To assess implications we quantified runoff of two herbicides, fluometuron and pendimethalin, and applied preemergence after planting cotton on Tifton loamy sand. Rainfall at constant and variable intensity patterns representative of late spring thunderstorms in the Atlantic Coastal Plain region of Georgia (USA) were simulated on 6-m^2 plots under strip- (ST) and conventional-tillage (CT) management. The variable pattern produced significantly higher runoff rates of both compounds from CT but not ST plots. However, on an event-basis, runoff totals (% applied) were not significantly different, with one exception: fluometuron runoff from CT plots. There was about 25% more fluometuron runoff with the variable versus the constant intensity pattern ($P = 0.10$). Study results suggest that conduct of simulations using variable intensity storm patterns may provide more representative rainfall simulation-based estimates of pesticide runoff and that the greatest impacts will be observed with CT. The study also found significantly more fluometuron in runoff from ST than CT plots. Further work is needed to determine whether this behavior may be generalized to other active ingredients with similar properties [low K_{oc} (organic carbon partition coefficient) ~100 mL g^{-1}; high water solubility ~100 mg L^{-1}]. If so, it should be considered when making tillage-specific herbicide recommendations to reduce runoff potential.

P ESTICIDE runoff research over the past 40 yr has relied heavily on rainfall simulation (Wauchope, 1978; Leonard, 1990; Fawcett et al., 1994; Capel et al., 2001). While advantages of these studies are widely recognized, limitations are often noted and concern persists that results may not accurately reflect the processes or magnitude of pesticide runoff caused by natural rainfall (Hill et al., 1991). Much of the discussion has focused on plot size since a majority of published simulated rainfall studies were conducted on "microplots" with areas ranging from 1 to 50 m^2 (Wauchope and Burgoa, 1995).

Some investigators have proposed use of "mesoplots," i.e., plots ranging from 500 to 700 m^2, to study pesticide runoff with the expectation that "mesoplots" more effectively simulate runoff and erosion processes that occur at larger (field) scales (Hendley et al., 1995; Sumner et al., 1996; Nett and Hendley, 2002). However, Wauchope et al. (2004) reported that 6-m^2 "microplots" and 620-m^2 "mesoplots" gave statistically similar results when fenamiphos runoff was evaluated under a uniform set of experimental conditions. No other published studies directly measuring pesticide runoff as function of plot size were identified in our literature search.

Another factor highlighted in discussions that have addressed potential differences in pesticide runoff due to simulated versus natural rainfall is rainfall intensity and pattern (Hill et al., 1991). Simulated rainfall is typically applied at a constant rate. Natural rainfall is rarely, if ever, constant and exhibits wide temporal and spatial intensity variation within and between storms. Bosch et al. (1999) documented this using a 30-yr rainfall record for the Little River Experimental Watershed (LREW) located in the Atlantic Coastal Plain region of Georgia (USA). Our laboratories and field study sites are located nearby. High rainfall rates, soil conditions, topographic features, and intensive pesticide use in the region make streams and rivers susceptible to adverse impacts from pesticide runoff (Kellogg et al., 1999).

Though limited to small scale laboratory-based investigation, a series of runoff studies conducted by Zhang et al. (1997) showed that storm intensity pattern may have substantial impact on pesticide runoff. Simulated rainfall in four intensity patterns was applied to 0.14-m^2 soil trays. Atrazine (6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-triazine-2,4-diamine) runoff for the pattern that reached peak intensity most quickly was twofold greater than other patterns. Myers et al. (1995) and Müller et al. (2004) also reported that increasing simulated rainfall intensity increased herbicide runoff. However, the intensity patterns in these studies were held constant for the duration of simulated storm events.

A need for field-based data to evaluate effects of simulated rainfall pattern on pesticide runoff motivated the work described in this report. We examined runoff of two herbicides commonly applied preemergence to cotton on plots under ST and CT management. Constant and variable rainfall intensity patterns based on late spring thunderstorm profiles were used.

T.L. Potter, C.C. Truman, D.D. Bosch, and T.C. Strickland, USDA-ARS, Southeast Watershed Research Laboratory, Box 748, Tifton, GA 31793. D.H. Franklin, USDA-ARS, J. Phil Campbell, Sr., Natural Resource Conservation Center, Watkinsville, GA. C.W. Bednarz, Dep. Crop and Soil Science, University of Georgia, Coastal Plain Experiment Station, Tifton, GA. T.M. Webster, USDA-ARS, Crop Protection and Management Research Unit, Box 748, Tifton, GA 31793. Mention of trade names or commercial products in this article is solely for providing specific product information and does not imply recommendation or endorsement by the authors, their respective institutions, or the USDA. Received 1 Dec. 2005. *Corresponding author (tpotter@tifton.usda.gov).

Abbreviations: AWC, antecedent water content; CT, conventional tillage; MDL, method detection limit; NT, no tillage; OC, organic carbon; %RPD, relative percent deviation; RSD, percent relative standard deviation; SD, standard deviation; ST, strip tillage.

MATERIALS AND METHODS

Study Site and Management

Soil properties (Tifton loamy sand, fine-loamy, siliceous, thermic, Plinthic Kaniudult, 3 to 4% slope) and other characteristics of the study site (located in Tift County, Georgia [31°26' N, 83°35' W]) were described in recent publications (Potter et al., 2003; Potter et al., 2004; Bosch et al., 2005). As in previous investigations, a 0.4-ha plot at the top of the slope was used for rainfall simulation experiments (Potter et al., 2003; Potter et al., 2004). This plot was equally divided across the slope by two tillage treatments, ST and CT, that were established in 1999. Strip-tillage is the most commonly used form of conservation tillage in the region. Cotton (*Gossypium hirsutum* L.) was produced in 1999, 2000, and 2001 growing seasons followed by peanut (*Arachis hypogaea* L.) in 2002. In the fall of each year, a rye (*Secale cearale* L.) cover crop was planted. The following spring the rye was killed by glyphosate application. The CT portion of the plot was then disked and bedded. On the ST portion, cotton or peanut was planted in 15-cm strips tilled into the cover crop residue surface mulch. Planting date, crop management, including fertilization and pest management, were based on University of Georgia recommendations and were followed uniformly for both tillage systems (Jost et al., 2005). After planting cotton, the herbicides Prowl 3.3 EC (BASF, Research Triangle Park, NC) and Cotoran 4L (Griffin LLC, Valdosta, GA) were tank-mixed and applied with a backpack sprayer to rainfall simulator plots installed within ST- and CT-managed areas. Active ingredients were pendimethalin [N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitro-benzenamine] and fluometuron {N,N-dimethyl-N'-[3-(trifluoromethyl)phenyl]-Urea}, respectively. Widespread use on cotton in the region and their contrasting runoff characteristics motivated selection of these herbicides for study (Potter et al., 2004). Application rate was nominally 2 kg ha^{-1} for fluometuron and 1 kg ha^{-1} for pendimethalin. Rates were measured using 7-cm diam. filter paper spray targets (4 per plot).

Rainfall Simulation

Plots were defined with stainless steel frames, 2 by 3 m, with the 3-m side positioned parallel to the rows. The 2-m side spanned two cotton rows with a wheel track between. Frames which were 15 cm high were pushed 5 cm into the soil. Runoff was collected from aluminum troughs installed at the downslope end of each plot. Simulated rainfall was applied with an oscillating nozzle rainfall simulator at two intensity patterns, constant and variable, for 70 min. The nominal drop diameter was 2.3 mm (Spraying Systems, Wheaton, IL). Both patterns gave the same rainfall volume. The storm size, 58 mm, has a 5-yr return interval in the region (Sheridan et al., 1979).The constant rate target intensity was 50 mm h^{-1}. The variable rate pattern was based on average characteristics of storms that occur from March through May in the region (Frauenfeld and Truman, 2004; Strickland et al., 2005). The target peak intensity was 2.6 mm min^{-1} and the time to peak was 19 min. Simulations began 24 h after planting and broadcast herbicide application. Water for simulations was obtained from a nearby irrigation well (Potter et al., 2003). During simulations, all runoff was collected in 1-L glass bottles and combined in 9-L stainless steel buckets in 5-min intervals. One to four buckets per interval were required depending on simulated rainfall intensity and runoff stage. After mixing the bucket(s), a clean 1-L glass bottle was filled using a stainless steel ladle. Bottles were sealed with Teflon-lined screw caps and within 1 h after completing each simulation, transferred to a laboratory refrigerator. A 500-mL acid washed polyethylene bottle was filled from the same bucket for nutrient analysis. The remaining water and sediment in the bucket(s) were poured into 1-L polyethylene bottles and reserved for total sediment and sediment organic carbon (OC) analysis. Collectively, the runoff placed in the 1-L polyethylene bottles is referred to as the "bulk sample" in the text. The weights of the bulk sample and subsamples taken for pesticide and nutrient analysis were summed to determine total runoff per 5-min interval. Buckets and ladles were decontaminated in the field by rinsing with 50:50 (v/v) isopropanol and deionized water and drying with paper towels. Composite soil samples at four depths, 0 to 2 cm, 2 to 8 cm, 8 to 15 cm, and 15 to 30 cm were collected before each simulation in herbicide-treated areas adjacent to each plot. Antecedent soil water content (AWC) was determined on a subsample of each by drying overnight at 105°C. All soil samples were stored in a −20°C freezer. A tipping bucket rain gauge (Global Water Instrumentation, Gold View, CA) coupled to a Campbell data logger (Campbell Scientific, Logan, UT) was positioned under the simulator during simulations to measure rainfall rates. Total rainfall during each simulation was computed using the rain gauge data and measurements of the total volume of water collected in three 15-cm diam. cans that were placed along the up-slope and sides of simulator plots.

Sample Preparation and Analysis

Runoff samples were filtered (Whatman GFF filters; 0.7-μ nominal pore size) within 2 d of collection. Filters and sediment were weighed and frozen. The filtrate was solid phase extracted using 6-mL by 0.2-g Oasis HLB cartridges (Waters Inc., Milford, MA). Filtered sediment, after thawing, was sequentially extracted (3 by 50 mL) with methanol. Spray targets were shaken with 25 mL of methanol. Additional sample preparation details were described by Potter et al. (2004). The bulk samples were acidified to pH ~2 with 12N HCl and allowed to stand at room temperature overnight. After decanting the clear supernate, bottles were dried overnight at 105°C and weighed. Sediment was then transferred to glass vials and reserved for OC analysis. Solvent extracts were concentrated to 10 mL under a directed stream of purified N$_2$ gas and analyzed by high performance liquid chromatography (HPLC)-tandem mass spectrometry (MS) using a Thermoquest LCQ DECA system (Thermoquest-Finnigan, San Jose, CA) equipped with an atmospheric pressure chemical ionization (APCI) interface. The HPLC column, which was 150 by 4.6 mm Gemini (5μm C18, 110Å), was purchased from Phenomenex (Palo Alto, CA). The HPLC flow rate during gradient elutions with 0.1% (A) formic acid and (B) methanol was 1 mL min^{-1}. Initial conditions, 90% A and 10% B, were increased linearly to 10% A and 90% B in 15 min and held isocratic for 4 min. Before analysis of each set of 54 samples, MS response was optimized for (M+H)$^+$ adducts of fluometuron (m/z$^+$ = 233) and pendimethalin (m/z$^+$ = 282) by infusing a mixture of two compounds (10 μg mL^{-1}) at 5 μL min^{-1} into the HPLC column effluent upstream of the APCI interface. Method detection limits (MDL), which were based on the low concentration standard (0.010 μg mL^{-1}) in each calibration, were 0.1 μg L^{-1} for water, 0.002 μg g^{-1} for soil, and 0.005 to 0.1 μg g^{-1} for sediment depending on the mass recovered by filtration. Dried sediment recovered from bulk samples was analyzed for OC using a Carlo-Erba Model NA1500 II CN-analyzer (Carlo-Erba Instruments, Milan, Italy). Analytical pesticide standards were purchased from Chem Service (Chester, PA). All other chemicals and supplies were obtained from Fisher Scientific (Hampton, NH).

Quality Control

Pendimethalin concentration was below the MDL in "blank" water samples collected from the simulator holding tank before each simulation. Fluometuron was detected (0.2 to 1.2 $\mu g\ L^{-1}$) in 9 of 12 of these "blanks." Given runoff volumes, the maximum "blank" concentration represented 0.4 to 3% of total fluometuron runoff; thus, impact on results was small. Matrix spikes were prepared by addition of 50 μL of a 100-μg mL^{-1} solution of fluometuron and pendimethalin (in methanol) to 1-L duplicates of "blanks." The average $\pm$ 1 standard deviation (SD) fluometuron recovery was 93 $\pm$ 15% and pendimethalin, 83 $\pm$ 19%. Precision of water sample analyses was evaluated by splitting filtrate of the runoff sample collected during the 15- to 20-min time step in each simulation into two equal volume aliquots and analyzing aliquots separately. The relative percent deviation (%RPD), computed using the ratio of the difference of each pair of values by their average, was 9.0 $\pm$ 7.1% for fluometuron and 11 $\pm$ 6.8% for pendimethalin. Data sets with duplicate %RPD less than 20% generally meet regulatory performance criteria (USEPA, 2000). Spike recoveries from filter paper used for spray targets were fluometuron, 107 $\pm$ 4.7% and pendimethalin, 108 $\pm$ 4.7%. Soil duplicate and spike recovery data were obtained from a concurrent field dissipation study on plots adjacent to the site where rainfall simulations were conducted. Fluometuron and pendimethalin spike recoveries were 93 $\pm$ 12% and 86 $\pm$ 15% and %RPD of duplicates were 14 $\pm$ 17% and 12 $\pm$ 11%, respectively. These results were assumed to describe analytical performance for soil and sediment sample analyses.

Data Analysis

Filtered sediment weight was divided by 1.2, a factor determined in prior rainfall simulation studies on Tifton soil, to account for water retained (Potter et al., 2003). Visual observations while handling runoff samples in the field indicated that there was rapid settling of coarse sand-size particles in sample collection buckets. Further, comparison of filtered sediment with corresponding bulk sediment concentration measurements indicated that mixing techniques did not effectively or uniformly resuspend all sediment in composite runoff samples. Overall, the filtered sediment averaged 40 $\pm$ 17% of the sediment in bulk samples. Herbicide residues were only measured in filtered sediment. Given potential uncertainties associated with the assumption that the total herbicide concentration in bulk sediment (sum of suspended and settled sediment) was equal to the concentration measured in filtered sediments, we chose to compute fluometuron and pendimethalin in bulk samples using Eq. [1] and [2]. This approach assumed linear equilibrium partitioning with OC. Literature average K_{oc}s where 16 400 $\pm$ 9400 mL g^{-1} was used for pendimethalin (Zheng and Cooper, 1996; USEPA, 1997; Pedersen et al., 1995) and 120 $\pm$ 40 mL g^{-1} for fluometuron (Gaston et al., 2003; Suba and Essington, 1999; Willan et al., 1997; Mueller et al., 1992; Gaston and Locke, 1995; Novak et al., 1996) were used. Equation [1] provided an estimate of OC in filtered sediment (f_{Soc}) using K_{oc}s and measured dissolved (C_w) and sediment (C_S) concentration of each compound. Total bulk sediment concentration (C_{sT}) of the compounds was then determined with Eq. [2] using computed f_{Soc}, the measured OC fraction in bulk sediment (f_{Toc}), corresponding K_{oc}, measured C_w, and measured bulk- and subsample sediment concentrations (C_{Ssed} and C_{Tsed}).

$$f_{Soc} = \frac{C_S}{C_W \times K_{OC}} \tag{1}$$

$$C_{sT} = \frac{[C_W \times K_{OC}(C_{Tsed} \times f_{Toc} - C_{Ssed} \times f_{Soc})]}{C_{Tsed}}$$
$$+ \frac{(C_S \times C_{Ssed})}{C_{Tsed}} \tag{2}$$

With the exception of fifteen (9% of total) sediment fluometuron analyses, all residue measurements were above MDLs. In computations, all values <MDL were assigned by insertion of half the MDL. Missing ($n = 15$) or rejected ($n = 8$) (Dixon test; $p = 0.05$) sediment OC values were assigned to the OC value for the next sample collected or by interpolation between values for samples collected immediately before and after. Unpaired t tests were used to evaluate differences in means of runoff responses by tillage and simulated rainfall intensity pattern using SigmaStat 3.1 (Systat, 2004). Slopes of linear regression lines were compared using the analysis of covariance function in StatMost (StatMost, 2005). All test statistics were evaluated at $P = 0.05$ unless otherwise noted.

RESULTS AND DISCUSSION

Rainfall, AWC, Runoff, and Soil Loss

Total rainfall measured for the duration of simulations was within 3 to 11% of the target (58 mm) across all plots. Differences in means of rainfall amounts between plots by tillage (2 to 7%) and rainfall pattern (1 to 4%) were small and not significant (Table 1). In addition, intensity patterns were relatively uniform and close to targets (Fig. 1). The average peak intensity (based on 5-min sampling intervals) was 2.0 $\pm$ 0.7 during variable intensity simulations compared to a target of 2.6 mm min^{-1}. For constant intensity simulations, the corresponding average was 1.0 $\pm$ 0.1 and with the target 0.9 mm min^{-1}. Generally the variable pattern peak intensity was about twofold greater than the constant pattern with the peak in the variable rate occurring between 20 and 25 min (Fig. 1). The target time-to-peak was 19 min. The apparent difference in the target and measured values was due to the fact that rainfall amounts were summed and plotted in 5-min intervals to correspond with runoff sample collection intervals (Fig. 1 and 2). By handling data in this way, the apparent time-to-peak was shifted to a longer time and peak intensity was reduced.

The other parameter likely to impact reproducibility among simulations, AWC, was also relatively uniform. The average of depth integrated (0- to 30-cm) values spanned a relatively narrow range, 5.6 to 6.2%, and RSDs by treatment block (tillage-rainfall intensity) were small (9 to 22%) (Table 1).

Runoff for simulations conducted with variable intensity rainfall reflected the intensity pattern. The time-to-peak runoff, between 25 and 30 min, occurred in the sample collection interval after peak rainfall intensity (20 to 25 min) was reached (Fig. 1). When constant intensity rainfall was applied, runoff rate steadily increased until the simulation was terminated (Fig. 1). From CT plots peak runoff was about 1.6-fold greater for the variable when compared to the constant intensity pattern. No difference in peak runoff rate for the two intensity patterns was observed on ST plots.

Table 1. Antecedent soil water content (AWC) and event-based summary of rainfall, runoff and soil loss by tillage and simulated rainfall intensity pattern.†

Tillage	Rainfall pattern	Rainfall	Runoff	Soil loss	AWC‡
		mm	%	g m^{-2}	%
Strip	constant	64.3 (3.7)	23.2 (2.2)§	64 (8)§#	5.8 (0.7)
Strip	variable	63.8 (2.5)	20.4 (3.1)¶	84 (9)¶#	5.6 (0.5)
Conventional	constant	60.0 (3.8)	50.5 (2.2)§	250 (50)§	6.1 (0.9)
Conventional	variable	62.7 (3.2)	44.8 (5.4)¶	290 (110)¶	6.2 (1.4)

† Average (standard deviation).
‡ Depth integrated (0 to 30 cm) gravimetric water content.
§ Significant difference for tillage treatments for corresponding constant rainfall pattern.
¶ Significant difference for tillage treatments for corresponding variable rainfall pattern.
Significant difference for rainfall pattern for corresponding ST plots.

Comparisons by tillage showed that the average CT plot peak runoff rate was 2.7-fold greater for the variable rainfall pattern and 1.6-fold greater for the constant pattern relative to ST plots. In total, the constant and variable intensity patterns yielded 20 to 23% on ST and 45 to 51% on CT plots of rainfall in runoff, respectively (Table 1). Tillage-related runoff differences in means were significant but runoff differences due to the two rainfall intensity patterns were not.

Soil loss followed the same trends as runoff with peak soil loss on plots receiving variable intensity rainfall occurring soon after peak rainfall intensity was reached (Fig. 2). Soil loss on plots receiving constant intensity rainfall changed more gradually with peak soil loss at 35 to 45 min with moderate decline in soil loss rate thereafter (Fig. 2). On both CT and ST plots the peak rate of soil loss was about threefold greater for the variable versus the constant intensity rainfall pattern. Means were signifi-

cantly different for ST plots. The difference in soil loss rate means due to rainfall pattern on CT plots, although greater, was not significant since results between plots were more variable. Results by tillage showed large and significant differences in means for both rainfall intensity patterns for peak and total soil loss for the simulation period (Table 1). Conventional tillage was about 4 times greater than total ST plot soil loss.

In sum, the variable pattern produced significantly higher peak runoff and soil loss rates. Significant differences in tillage-related response were also noted with CT > ST plot peak rates. When soil loss and runoff data were summed for the duration of the simulations, rainfall intensity pattern differences in runoff and soil loss were small and not significant. In contrast, tillage impacts were clear. Conventional tillage plots yielded about twofold greater runoff and fourfold greater soil loss than ST plots.
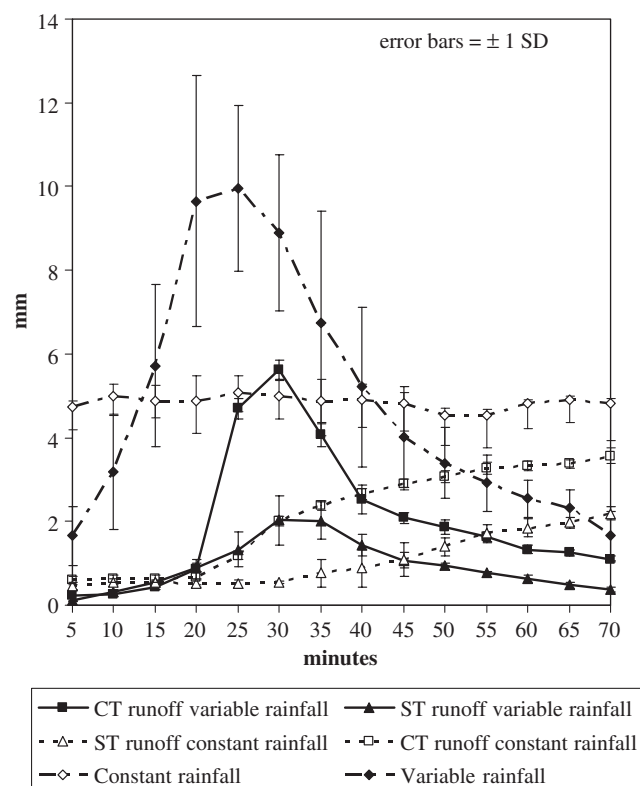
Fig. 1. Average rainfall amounts for constant and variable intensity simulated rainfall patterns and runoff from plots as a function of tillage and simulated rainfall intensity pattern.
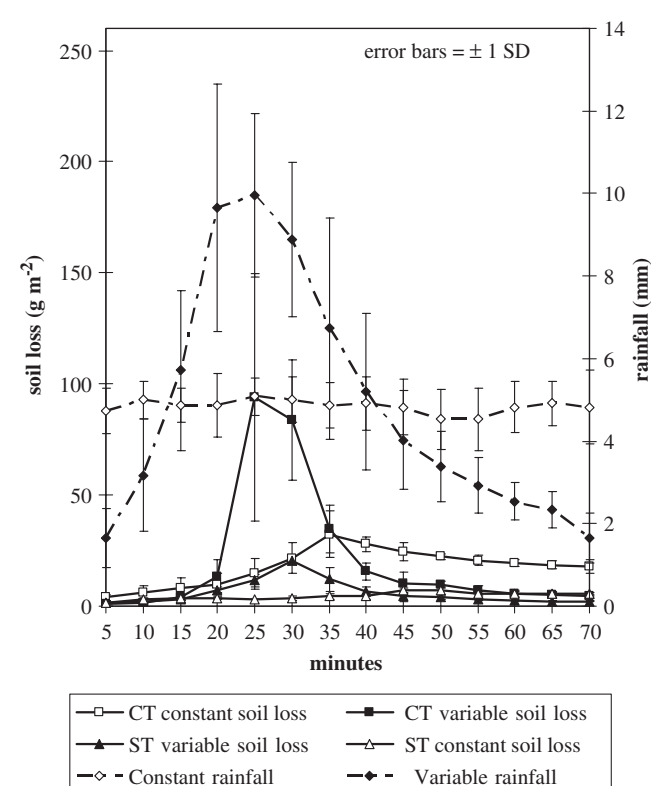
Fig. 2. Average rainfall amounts for constant and variable intensity simulated rainfall patterns and soil loss as function of tillage management and rainfall intensity pattern.

Pendimethalin Runoff

Pendimethalin runoff reflected trends in soil loss and runoff volumes. Concentrations were much greater in CT plot runoff (Fig. 3) and at the end of simulations; the total mass of pendimethalin in runoff was up to 10-fold greater from CT when compared to ST plots (Tables 2 and 3). Greater CT runoff was attributed to pendimethalin's high K_{oc} (average = 16 400 mL g^{-1}) and tendency to bind to sediment, and much higher CT plot soil loss. Peak pendimethalin concentration in runoff from CT plots under both simulation intensity patterns (Fig. 3) coincided with peak rates of soil loss (Fig. 2). Overall the sediment-transported fraction (difference between total and dissolved) accounted for 60 to 70% of pendimethalin runoff from CT and 30 to 40% of total pendimethalin from ST plots (Tables 2 and 3).

Differences in tillage and rainfall intensity pattern responses are reflected in the plot of cumulative pendimethalin runoff (% of applied) and runoff volume (Fig. 4). Slopes of linear regression lines fit to CT were eightfold greater than ST plots under constant rainfall with the difference about 12-fold greater for the variable rate rainfall treatment (Table 4). Results emphasized pendimethalin's much greater runoff tendency with CT management and that variable rate rainfall on CT plots may produce higher pendimethalin runoff rates than simulations conducted using a constant intensity pattern. The latter was inferred from the observation that the slope of the line for the variable was significantly greater that the one derived using constant intensity runoff data for CT plots. This was the case even though the r^2 (0.73) for

the variable rate regression line was relatively low (Table 4). The low r^2 reflected the relatively wide variation in soil loss on CT plots receiving variable rate rainfall. The RSD was 37% compared to 25% for the constant intensity rainfall treatment (Table 2). Greater variation in soil loss under the variable pattern was anticipated given greater uncertainty in rainfall amounts (Fig. 2) and the more than twofold greater peak rainfall intensity for the variable pattern. Slopes of regression lines derived from variable and constant intensity rainfall simulations on ST plots were equal, indicating that under ST management rainfall intensity had little or no impact on pendimethalin runoff.

Another notable feature of CT plot pendimethalin runoff was its magnitude. For the duration of the simulation periods, up to 5% of pendimethalin applied was measured in runoff (Table 3). This value was relatively high when compared to typical values (~1%) reported in pesticide runoff studies (Wauchope, 1978; Leonard, 1990). The high losses found in our study may be partly explained by the manner in which total sediment concentrations were computed using Eq. [1] and [2]. The K_{oc} values reported in the literature were used in computations. Values span a relatively broad range with RSD ~60% (Zheng and Cooper, 1996; USEPA, 1997; Pedersen et al., 1995). When factored into computations, uncertainty associated with ± 1 SD in pendimethalin K_{oc} was ± 34% to ± 38% for CT and ± 11% to ± 18% for ST plot volume-weighted concentrations (computed by dividing the mass loss during simulations by total runoff volumes). The difference in the magnitude of the uncertainty between tillage treatments was due to the large differences in sediment loads (3- to fourfold).

Other uncertainty in concentration and runoff estimates was likely due to the assumption of equilibrium for both adsorption and desorption reactions in computations (Eq. [1] and [2]). Moderate to low impact was inferred from sensitivity analyses for chlorpyrifos in the kinetic adsorption algorithm in the Root Zone Water Quality Model (Ma et al., 2004). A ± 25% variation in the kinetic sorption rate constant resulted in −0.1 to 0.04% variation in annual runoff mass. The chlorpyrifos K_{oc}, used in these calculations, 6070 mL g^{-1}, was within the range of values reported for pendimethalin; thus, pendimethalin and chlorpyrifos runoff behavior are likely similar.

Data showed that pendimethalin runoff from CT plots was dominated by sediment transport, dissolved phase transport, and measured 30 to 40% of the total, and 1.5 to 1.6% of applied, which were relatively high values (Table 3). Further, when compared to ST total dissolved losses from CT plots, they were about sevenfold greater. This was the case even though CT runoff volume was only about twofold greater than from ST plots (Table 2). This was likely explained by spray interception by cover crop residue on ST plots and very low pendimethalin washoff rates from the residue. Low rates of washoff were indicated in a report by Gaston et al. (2003). Three successive applications of 50 mm of simulated rainfall removed <0.6% of applied to cover crop residue and other dried plant materials. This suggests that pendi-
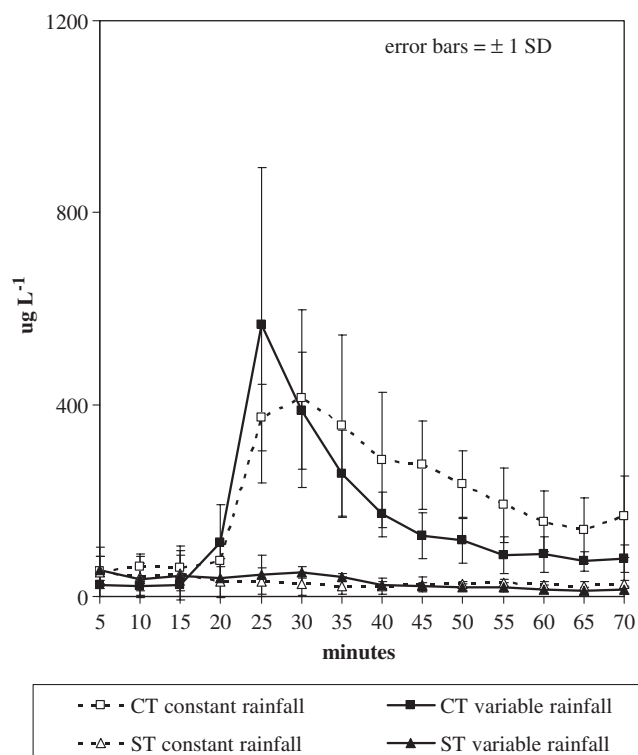

Fig. 3. Average pendimethalin concentration in runoff as a function of tillage and rainfall intensity pattern.

Table 2. Fluometuron and pendimethalin application rate and event-based volume-weighted concentration in runoff by tillage and rainfall intensity pattern.†§

Tillage	Rainfall pattern	Fluometuron			Pendimethalin		
		Applied	Concentration		Applied	Concentration	
			Dissolved	Total‡		Dissolved	Total
		μg cm^{-2}	μg L^{-1}		μg cm^{-2}	μg L^{-1}	
Strip	constant	18 (1)	210 (140)	210 (140)	11 (0.2)	19 (11)¶	27 (14)¶
Strip	variable	20 (6)	200 (20)#	200 (20)#	12 (3)	19 (8)#	33 (15)#
Conventional	constant	28 (6)	50 (20)	53 (20)	16 (3)	90 (50)¶	220 (90)¶
Conventional	variable	28 (10)	80 (30)#	80 (30)#	16 (7)	80 (20)#	260 (100)#

† Average (standard deviation).
‡ Total = dissolved plus computed sediment-bound (K_{oc} used in calculation = literature average).
§ Volume-weighted concentration computed by dividing the mass of the compound detected in runoff by total runoff volume.
¶ Significant difference for tillage treatments for corresponding constant rainfall pattern.
# Significant difference for tillage treatments for corresponding variable rainfall pattern.

methalin, which is intercepted during broadcast application, is strongly bound to the crop residue and is essentially unavailable for washoff. This may explain reduced pendimethalin weed control efficacy in ST when compared to use under CT management (Johnson et al., 2002).

Fluometuron Runoff

Fluometuron runoff was similar to pendimethalin relative to simulated rainfall intensity patterns. ST did not differ, but CT plot responses did. Conventional-tillage plot means of mass loss, evaluated as % of applied and volume-weighted concentration, and the slope of the linear regression line fitted to the cumulative percent loss and runoff volume data were significantly greater for plots receiving variable versus constant intensity simulated rainfall (Tables 2, 3, and 4; Fig. 5).

Generally variable rate rainfall produced about 25% more fluometuron runoff than constant rate rainfall on CT plots (Table 3). A possible explanation was that the constant intensity pattern produced more fluometuron leaching at the earliest stage of simulations. In the first 10 min of all simulations there was little runoff (Fig. 1). During this interval, plots under the constant pattern received about twofold more simulated rainfall as those under the variable pattern, thus there was twofold greater infiltration with the constant intensity pattern. This likely resulted in more fluometuron moving deeper into the soil and may have made less available for runoff. Fluometuron's relatively high water solubility ($\sim$100 mg L^{-1}) and low K_{oc} ($\sim$100 mL g^{-1}) combined with low (0.5 to 1.0%) soil OC explain the compound's

relatively high leaching potential at the study site (Potter et al., 2004).

As indicated, total ST plot fluometuron runoff did not exhibit significant rainfall intensity differences (Table 3). This was due to relatively high runoff from one ST plot under constant intensity rainfall. When results for this plot were removed from data analysis, fluometuron ST plot runoff under constant rainfall averaged 1.1%. This value was significantly ($P = 0.10$) less than the corresponding ST variable rate rainfall average and followed the same trend that was observed with runoff from CT plots, i.e., that variable rate rainfall yielded more fluometuron runoff. There was a basis for rejection since Grubbs and Dixon tests ($P = 0.05$) indicated that the high value in question was an outlier (Taylor, 1990).

While rainfall intensity pattern responses for pendimethalin and fluometuron runoff were similar, tillage-related responses were opposite. Much higher fluometuron concentration was observed in runoff from ST plots with values 3- to fourfold higher than from CT plots, during the time period when most of the runoff occurred (25 to 70 min) (Fig. 6). Thus when the mass loss of fluometuron (expressed as volume-weighted concentration and percent of applied) was evaluated for the duration of simulations, ST was greater than CT plot values (Tables 2 and 3) even though runoff volume (twofold) and soil loss (3- to fourfold) were greater from CT plots. Means of fluometuron mass loss were significantly greater for ST plots under variable intensity simulated rainfall (Tables 2 and 3). The corresponding ST means were greater than CT plot means for the constant intensity rainfall treatment, but differences were not significant

Table 3. Fluometuron and pendimethalin runoff expressed as percent of applied.†

Tillage	Rainfall pattern	Fluometuron		Pendimethalin	
		Dissolved	Total‡	Dissolved	Total
Strip	constant	1.9 (1.4)	1.9 (1.4)	0.3 (0.2)¶	0.4 (0.2)¶
Strip	variable	1.4 (0.4)¶	1.4 (0.4)¶	0.2 (0.2)#	0.4 (0.3)#
Conventional	constant	0.6 (0.2)§	0.6 (0.2)§	1.6 (0.6)¶	4.1 (1.1)¶
Conventional	variable	0.8 (0.1)§¶	0.8 (0.1)§¶	1.5 (0.4)#	5.0 (2.8)#

† Average (standard deviation); n = 3 plots.
‡ Total = dissolved plus computed sediment-bound concentrations.
§ Significant difference ($P = 0.1$) for rainfall pattern treatment on corresponding CT plots.
¶ Significant difference for tillage treatments for corresponding constant rainfall pattern.
# Significant difference for tillage treatments for corresponding variable rainfall pattern.
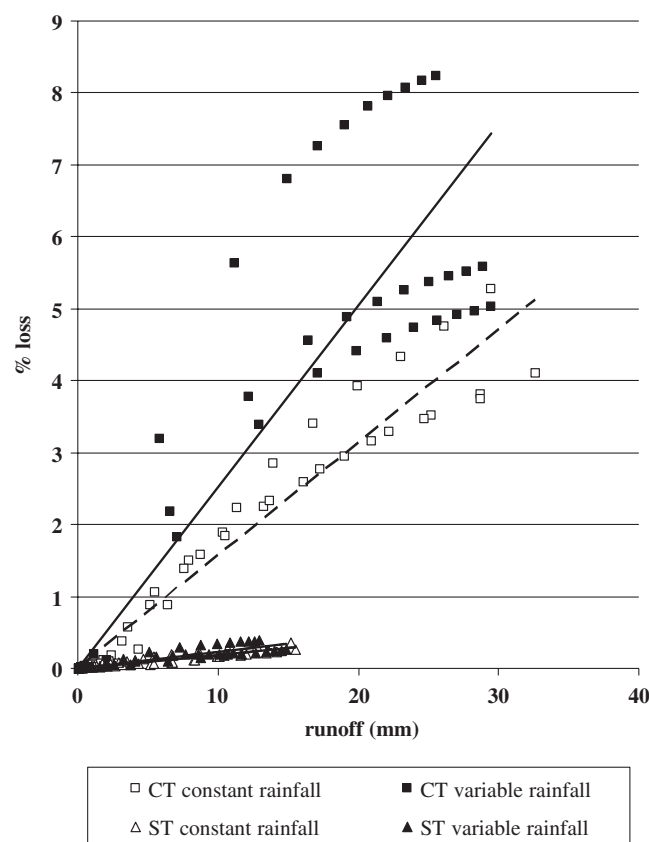
Fig. 4. Cumulative pendimethalin loss expressed as percent of applied versus cumulative runoff during simulations.

Fig. 5. Cumulative fluometuron loss expressed as percent of applied versus cumulative runoff during simulations.

due to relatively high variability in ST plot results (Tables 2 and 3).

Fluometuron runoff rate, when evaluated by comparison of the slopes of the regression lines fitted to cumulative fluometuron runoff versus cumulative runoff volume, followed the same trends (Fig. 5; Table 4). The rate of fluometuron loss from ST plots was about 3- to fourfold greater than from CT plots with the difference in the mean rates of ST plots significantly greater with variable intensity rainfall simulations.

Greater fluometuron runoff from ST when compared to CT plots has been reported in other studies (Baughman et al., 2001; Potter et al., 2004). As observed in our investigation, this was noted even though runoff volume and soil loss were substantially lower from ST than CT
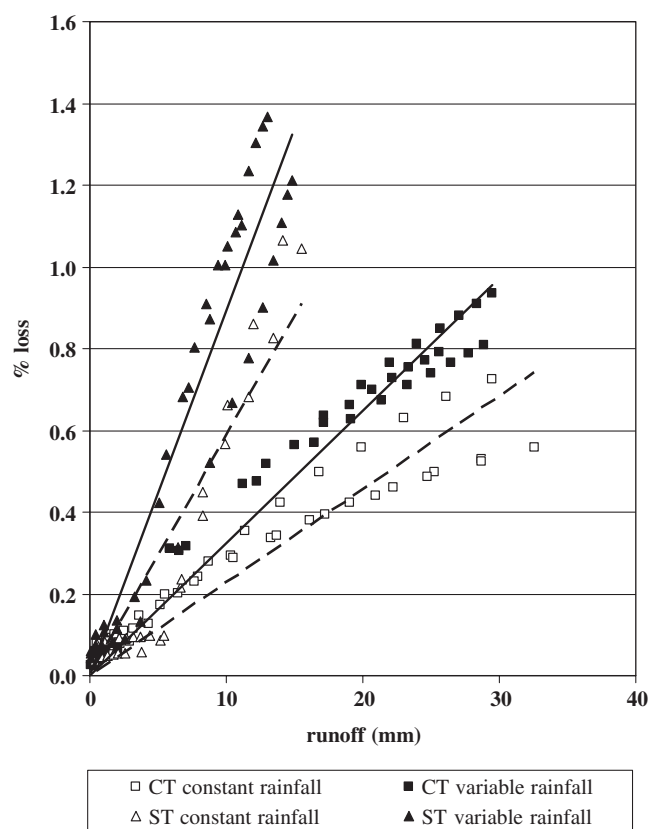
Table 4. Slope and correlation coefficients obtained by linear regression of cumulative percent of applied fluometuron and pendimethalin lost in runoff and cumulative runoff (see Fig. 4 and 5).

Tillage	Rainfall pattern	Fluometuron		Pendimethalin	
		r^2	Slope	r^2	Slope
Strip	constant	0.73	0.08‡	0.74	0.02‡
Strip	variable	0.90	0.09§	0.83	0.02§
Conventional	constant	0.87	0.02†‡	0.94	0.16†‡
Conventional	variable	0.97	0.03†§	0.73	0.25†§

† Significant difference for rainfall pattern on corresponding CT plots.
‡ Significant difference for tillage treatments for corresponding constant rainfall pattern.
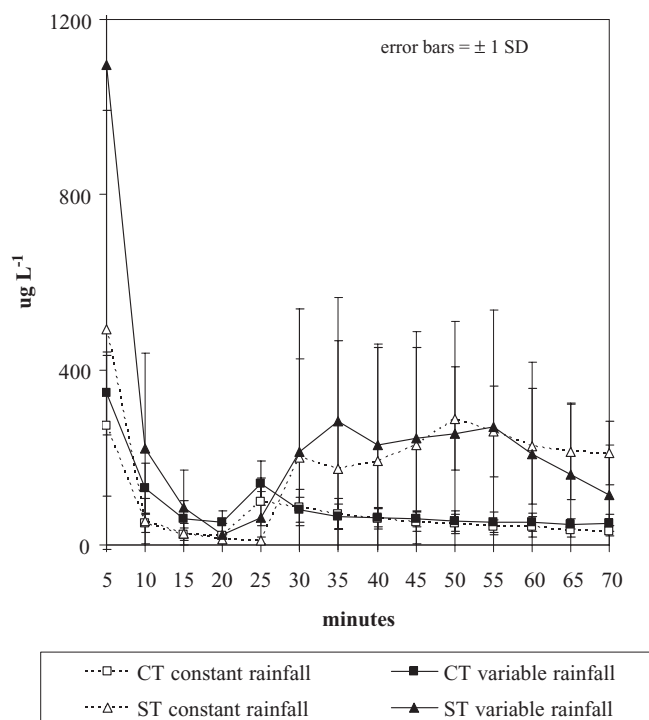§ Significant difference for tillage treatments for corresponding variable rainfall pattern.

plots. Generally ST was greater than CT plot loss because ST plot fluometuron concentrations were greater than differences in runoff volumes between tillage treatments. Soil loss differences did not impact total fluometuron runoff due to the compound's weak binding to soil and sediment. This is reflected in the fluometuron's relatively high water solubility and low K_{oc} described above, and measurements which showed that nearly all fluometuron in runoff was dissolved (Tables 2 and 3).

Fluometuron's K_{oc}, which describes absorption on organic matter surfaces, also appears to explain its wash-off behavior from crop residue. Gaston et al. (2001) reported that the fraction of fluometuron applied to cover crop residue that was washed off with 50 mm of simulated rainfall was about 20% of that applied with the amount increasing to a cumulative total of 40 to 60% after three 50-mm rainfall applications. This was in contrast to pendimethalin. Under similar conditions, <0.6% was washed off (Gaston et al., 2003). Pendimethalin's literature average K_{oc} is ~160-fold greater.

In turn, fluometuron's crop residue washoff characteristics may explain observations that total ST was greater than CT plot runoff of the compound. On ST plots, the crop residue likely intercepted a substantial portion of the fluometuron applied. The Gaston et al. (2001) data indicate that a portion of intercepted fluometuron (~20%) would have been released to the soil surface during simulations. The timing of the release relative to changes in infiltration and initiation of plot runoff likely resulted in relatively high fluometuron

Fig. 6. Average fluometuron concentration in runoff as a function of tillage and rainfall intensity pattern.

tion-based estimates of pesticide runoff of due to natural rainfall. The greatest difference will likely be observed when CT is practiced. While rainfall intensity pattern pesticide runoff differences were not observed with ST, results showed that runoff of relatively water-soluble pesticides, like fluometuron, might be greater from ST than from CT plots even though total runoff volume from ST plots is substantially lower. Further work is needed to determine whether this behavior may be generalized. If so, it should be considered when making tillage-specific herbicide recommendations to reduce runoff potential.

concentration in runoff. Furthermore, on CT plots, at the earliest stage of simulations, a relatively high infiltration rate would promote fluometuron leaching and remove proportionally more fluometuron from the runoff extraction zone than on ST plots. Thus, less fluometuron would be available for runoff from CT than ST plots.

Fluometuron runoff behavior was consistent with reports of greater atrazine runoff from no tillage (NT) and ST when compared to bare soil (Sauer and Daniel, 1987; Myers et al., 1995; Mickelson et al., 2001). Atrazine has a K_{oc} and water solubility comparable to fluometuron, and like fluometuron is subject to leaching in soils with low OC content. This suggests that other herbicides with similar properties may behave similarly and provides a mechanistic explanation of why pesticide runoff associated with reduced tillage is sometimes higher than with conventional tillage (Fawcett et al., 1994; Myers et al., 1995; Baughman et al., 2001; Potter et al., 2004).

CONCLUSIONS

The interaction between simulated rainfall intensity pattern and herbicide runoff that was observed has implications for the design and implementation of rainfall simulation-based investigations of pesticide runoff. With CT management, the runoff rate of the two herbicides studied was significantly greater for a variable when compared to a constant intensity rainfall pattern. Total runoff of fluometuron, the compound that had relatively high leaching potential and low K_{oc}, was also significantly greater for the variable pattern. Thus, simulations using intensity patterns that reflect natural rainfall characteristics have the potential to improve rainfall simula-

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